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A SMALL HELIUM LIQUIFIER WHICH PROVIDES CONTINUOUS COOLING BASED ON CYCLED ISENTROPIC EXPANSION

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This simple cryocooler provides a small reservoir of liquid helium at a stable temperature of 4.2K. It uses a novel adaptation of the Simon expansion cryocooler to provide continuous cooling. Operation is in a four stage cycle: (1) A closed vessel of helium under high pressure is cooled to 12K using a conventional Gifford-McMahon closed-cycle cryocooler. (2) The pressure is released adiabatically providing cooling to 4.2K. (3) Liquid helium is collected in a second, well insulated, vessel. (4) The first vessel is re-pressurized. The cycle time is 15-30 minutes. In this manner, a pool of liquid helium is continuously maintained in the second vessel, with a temperature stability of 0.03 degrees. The continuous cooling power available is 3mW. This design provides simplicity and reliability through the absence of any orifices or moving parts at cryogenic temperatures except for the conventional Gifford-McMahon cryocooler.

Key words: Cryocoolers; small; liquifiers; helium liquifiers; liquid helium; helium; isentropic expansion; Simon; Gifford-McMahon; refrigerators.

1. Introduction

Historically, the development of low temperature physics and its applications have rapidly followed the development of cryogenic refrigerators, or "cryocoolers". There is now a host of applications of low temperatures, especially those using superconductors, which are not economical, given the high cost of most commercial helium liquifiers. Those applications which are economical generally rely on the presence of a large helium liquifier in their vicinity. Driven by this need for inexpensive helium liquifiers our group has developed a number of different cryocoolers. This paper describes one of our cryocoolers. For a more complete review of our work and that of others in this field the reader is referred to several recent reviews of progress in the field of inexpensive helium liquifiers [1,2,3].

We have built a simple and inexpensive helium liquifier using a commercial two stage Gifford-McMahon cycle cryocooler (of the type used in cryopumps) for the initial stages of cooling. The novelty of our cryocooler is that it is able to provide continuous cooling at liquid helium temperature, by recycling an adiabatic expander. The liquifier is useful for many applications with modest cooling power requirements, i.e. the operation of small superconducting devices, infra-red detectors, laboratory measurements of material properties at low temperatures and neutron diffraction measurements.

2. Principles of operation

2.1 Adiabatic Expansion

Helium is liquified in our cryocooler by adiabatic (isentropic) expansion of previously cooled, high pressure helium gas. This technique was exploited by Simon [4] in 1932 using liquid hydrogen to precool the compressed gas. In our cryocooler, an expansion volume of 10 ml is cooled

to 12K, by the two stage Gifford- McMahon cryocooler, while filling with helium at a pressure of 6.2 MPa (62 bars). Once cooled, the mass or supercritical gas in the expansion volume will be 1.6 g [5]. When an exhaust valve is opened to allow this gas to escape (to the atmosphere) to a pressure of 0.1 MPa cooling is produced in the expansion volume. This process is very nearly adiabatic because at these low temperatures the specific heat of the metal vessel is negligible compared to the specific heat of helium gas. At the 0.1MPa pressure, the expansion volume will contain 1.7 ml of liquid helium with the remainder gaseous for a total of 0.35 g.

2.2 Principle of cycled adiabatic expansion

The liquefaction process described above is of a one-shot nature. After the liquid generated has been boiled off, the temperature rises. In order to recycle the expansion volume it must be filled with compressed helium gas. Since the refill gas comes from outside the apparatus it is initially warm. In addition, the process of compressing the gas adiabatically produces heating. The expansion volume must be cooled to 12K again by the two stage Gifford-McMahon cryocooler before the next expansion and liquefaction cycle may commence. In this manner the adiabatic expansion may be cycled, but the temperature of the expansion volume will oscillate between 4.2K and 20K.

In order to echieve a constant temperature liquid helium bath, a separate, well insulated, container is attached to the bottom of the expansion volume to act as a liquid helium reservoir. This reservoir is replenished with liquid helium at each expansion phase of the cycle. During the compression phase, however, the liquid in this reservoir may be boiled to provide a continuous 4.2K temperature bath.

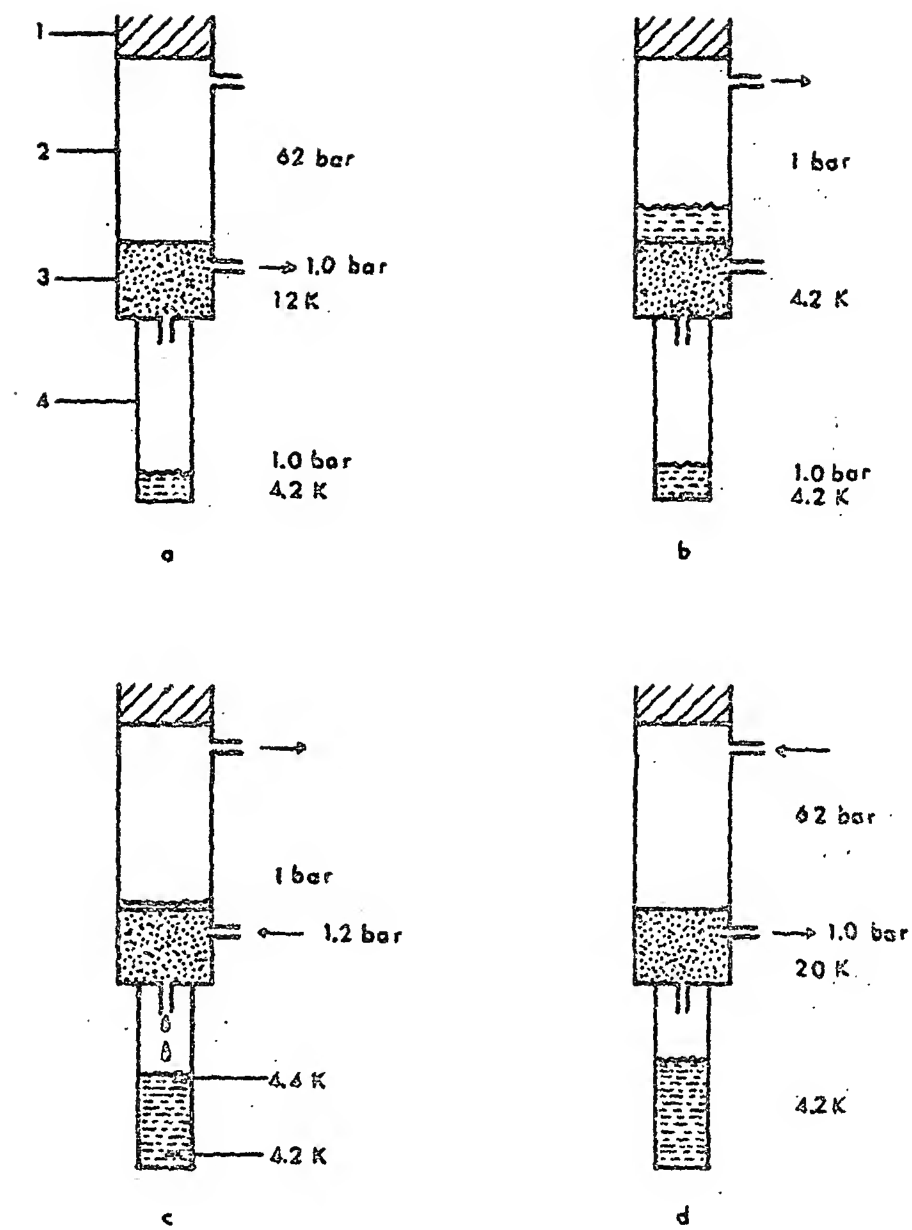
2.3 Principle of thermal diode

Proper operation of the liquid helium reservoir requires that it be in good thermal contact with the expansion volume during the expansion phase, but that it be thermally isolated during the compression phase. The natural tendency of cold helium to flow to the bottom of a container is used to provide this switching action in our cryocooler. The liquid reservoir is located directly below the expansion vessel. During the expansion phase a slight overpressure in the reservoir allows helium to condense on its cold top surface. This liquid then flows to the bottom of the reservoir. During the compression phase the expansion volume heats up to approximately 20K. This also heats the gas in the upper part of the insulation tube. However, due to the low thermal conductivity of helium and due to the natural stratification of the gas with the warm gas on top, little heat is conducted down to the liquid reservoir.

The function of the long insulation tube at the top of the liquid reservior is analogous to an electrical diode. When the top end is cold it conducts heat, either by natural convection currents or by liquefaction and boiling of helium. When the top end is hot it becomes a thermal insulator. The helium gas stratifies and convection currents cease.

2.4 Operating cycle

The operating cycle is shown in figure 1. There are four phases to the cycle. At (a), helium gas at a pressure of 6.2MPa (62 bars) is cooled to 12K using a conventional two-stage Gifford-McMahon closed cycle refrigerator. At (b), a valve at room temperature is opened allowing the gas to expand. The expansion is essentially adiabatic, since at 12K the specific heat of the stainless steel and copper high pressure expansion vessel is negligible compared to the heat of its gaseous helium contents. The cooling provided by the expansion results in the vessel remaining approximately one-sixth full of liquid helium. At (c), helium gas at a slight overpressure is piped through counterflow heat exchangers and enters the liquid reservoir. Good thermal contact with the bottom of the expansion vessel causes condensation of the incoming helium and evaporation of liquid helium in the expansion vessel. The cold helium produced by evaporation is piped through the counterflow heat exchangers and is vented to the atmosphere. In effect, liquid helium from the expansion vessel is "transferred" to the liquid reservoir, although there is no plumbing connection joining the two vessels. The final step in the cycle, (d), is that high pressure helium gas is forced back into the expansion vessel, figure 1(d). This compression raises the temperature of the expansion vessel to about 20K. At this stage of the cycle, gravity causes stratification to the helium gas - thermally insulating the liquid helium (4.2K) at the bottom of the liquid reservoir, from the relatively hot (20K) expansion vessel.



(a) --->	ADIABATIC EXPANSION 12K TO 4.2K	(b) --->	'TRANSFER' LIQUID HELIUM TO RESERVOIR	(c) --->	REPRESSURIZE EXPANSION VESSEL HEATING IT TO 20K	(d) --->	COOL EXPANSION VESSEL TO 12K	(a) --->
	1 MINUTE		4 MINUTES		2 MINUTES		8 MINUTES	

Figure 1 - Cycle of operation

1. 12K Cold finger of Gifford-McMahon cryocooler.
2. High pressure expansion volume.
3. Sintered copper heat exchanger.
4. Low pressure liquid reservoir.

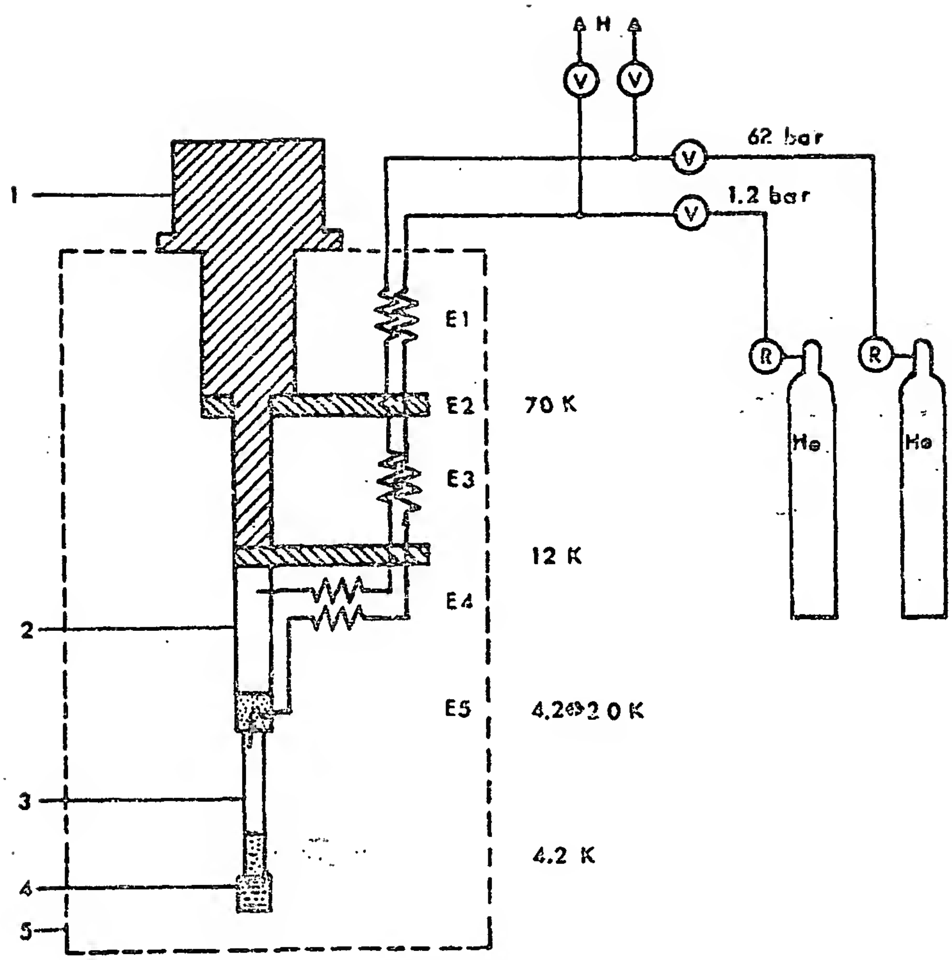


Figure 2 - Schematic diagram of cryocooler

1. 2-Stage, closed-cycle Gifford-McMahon cryocooler.
2. Expansion volume (high pressure).
3. Insulation tube.
4. Liquid helium reservoir (low pressure).
5. Vacuum vessel with heat shields (not shown).

R Pressure regulator valves.
V Electronically driven solenoid valves.
H To helium recovery.
E Heat exchangers.

2.5 Temperature stability in the liquid reservoir

The temperature in the pool of liquid helium in the reservoir is held stable at the boiling point of liquid helium (4.2K). In order to allow helium to condense the pressure in the reservoir is increased to about 0.12MPa (1.2 atmospheres) during the expansion phase. Condensation causes heating of the top layer of liquid helium to its boiling point at this new increased pressure (4.4K). However, the liquid lower down in the reservoir is not heated by condensation. The liquid helium stratifies with a thin warm layer on top. Heating of the liquid at the bottom of the reservoir is by thermal conduction through the liquid and by adiabatic compression of the liquid. The adiabatic compression term is only approximately 20 millidegrees. The thermal conduction term can be much larger. However, the high specific heat of liquid helium and its low thermal conductivity make thermal conduction through the liquid a very slow process. The variation in temperature δT at a depth x due to an abrupt change in temperature of ΔT at the surface is

given by,

$$\frac{\delta T}{\Delta T} = 1 - \operatorname{erf}\left(\frac{x}{2}\sqrt{\frac{\rho\ Cp}{\tau\ K}}\right)$$

where

$$\operatorname{erf}(u) = \frac{2}{\sqrt{\pi}}\int_0^u e^{-y^2}\,dy$$

is Gauss's error integral[6]. The specific heat of liquid helium per unit volume, at constant pressure is ρCp. The thermal conductivity of liquid helium is K and τ is the time elapsed since the temperature change on the surface.

For example, consider the 0.2 degree change in temperature at the surface of the liquid. The time required for that to cause a temperature change of 0.020 degree is one minute for a liquid helium depth of 0.3cm but is one hour for a depth of only 2.5cm.

In our cryocooler, the liquid reservoir is at a pressure above atmospheric for only 5 minutes during each cycle. Temperature fluctations due to warming of the liquid during this period are therefore substantially dampened once the liquid reservoir starts to accumulate a certain depth of liquid helium.

3. Cryocooler design

A schematic of the four-stage cryocooler is shown in figure 2. The first two stages of cooling, nominally 70K and 12K, are provided by a conventional laboratory Gifford-McMahon cycle crycooler. The third and fourth stage system is thermally connected to the two-stage crycooler. Helium gas lines go from room temperature to the third stage expansion vessel and to the fourth stage liquid helium reservoir. The two gas lines are not interconnected and their helium supplies are independent. Operation of the crycooler is achieved by cycling the pressures at the room temperature ends of the expansion vessel line and the liquid reservoir line.

For simplicity and ease of construction, the pressures are cycled by means of opening and closing electric solenoid valves. The gas lines are alternately charged from compressed gas cylinders and vented to a helium recovery system at one atmosphere pressure. Maximium pressures are set by regulator valves on the gas cylinders. They are set at 6.2MPa (62 bars) for the expansion vessel and 0.12MPa (0.02MPa above atmospheric) for the liquid helium reservoir line. The solenoid valves are controlled by an electronic cycle timing circuit. The rates of charging and venting are quite critical, they are set by manual valves.

The cycle timing is mainly determined by how long it takes the two-stage croycooler to cool the expansion vessel to a threshold temperature of approximately 12K. If the threshold is set too low then it takes a very long time to cool down and the cycle time becomes too long. If the threshold is set too high then very little, or no, liquid helium will be produced during the expansion phase. Typical cycle times are shown in figure 3.

The critical parameter in the design is the length of the time required to complete one cycle. If it takes too long then all the liquid in the reservoir will boil away before the next expansion (cooling) phase commences. During each cycle almost all of the helium gas in the expansion vessel is taken to room remperature then returned to below 12K. The minimum cycle time is mainly determined by how long it takes the two-stage crycooler to cool this mass of helium gas from 300K to 12K. This time is substantially reduced by using effective regenerators to utilize the cooling power of the escaping gasses of one cycle to cool the incoming gasses of the next cycle. The dimensions and masses of the heat exchanger-regenerators are given in table 1. Note that, effective regeneration is assured between 300K and 70K by 500 grams of stainless steel in exchanger E1. Regeneration below 70K is acheived by 850 g of lead shot in exchanger E3. These massive components lengthen the initial cooldown of the crycooler (by about 20 hours) but speed up the operating cycle rate. We have also tested a Simon expander without these regenerators. As expected, its minimum cycle time was too long (over one hour) to maintain a bath of liquid helium.

Another feature worthy of note is the use of the counterflow heat exchanger number E4 (12K-4.2K). This is essential in order for the liquid helium 'transfer', phase (c), to take place. Helium gas entering the liquid reservoir must be cooled to just above its boiling point before passing through the copper powder heat exchanger number E5. If this is not done the cooling power of the boiling liquid in the expansion vessel will be wasted in irreversible heat transfer to hot helium gas and no liquid will be collected in the reservoir.

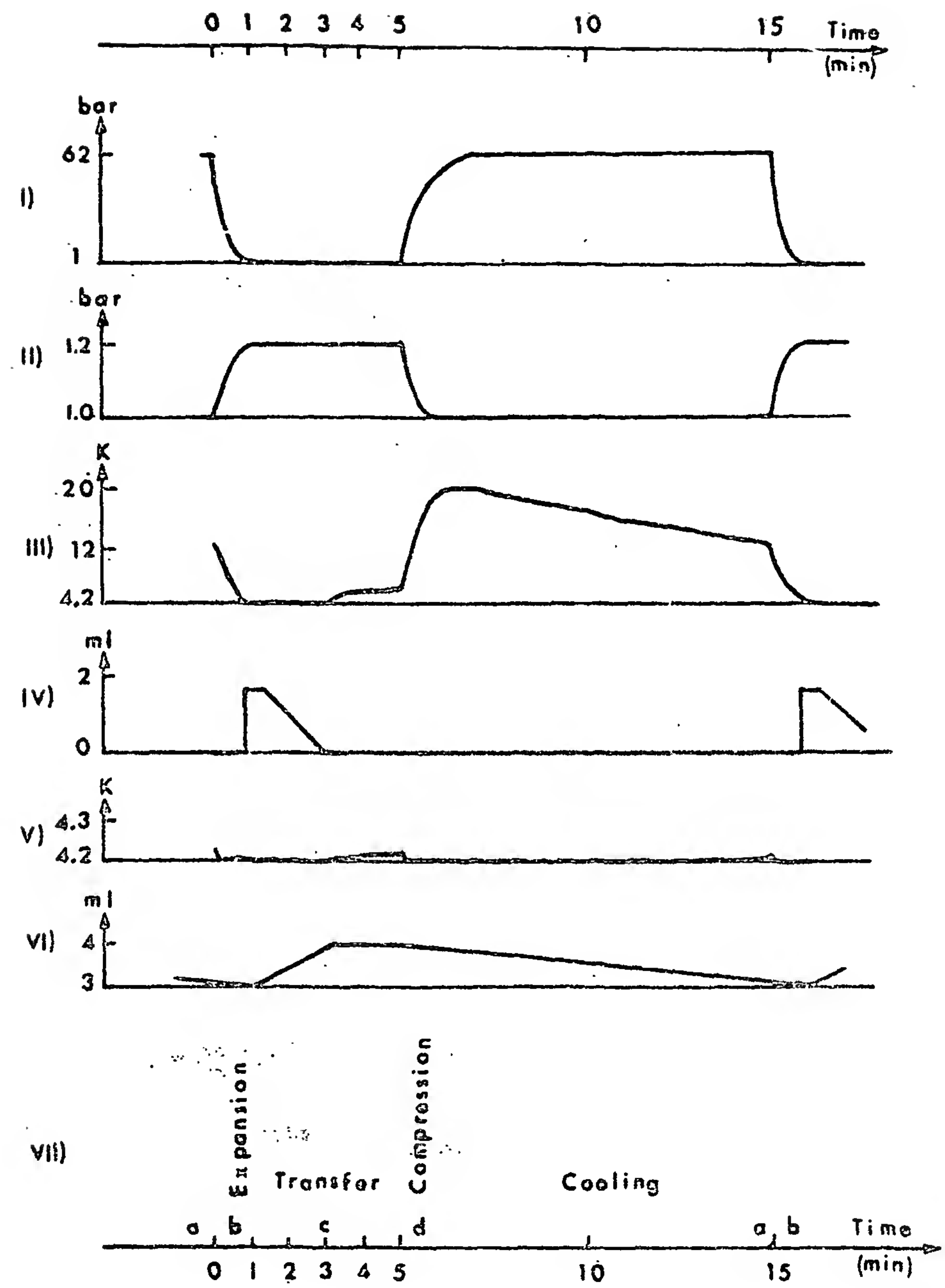


Figure 3 – Cryocooler cycle with no heat load

I) Pressure at the room temperature end of the expansion volume gas line.
II) Pressure at the room temperature end of the liquid reservoir gas line.
III) Measured temperature at the bottom of the expansion volume.
IV) Estimated volume of liquid helium in the expansion volume.
V) Measured temperature at the bottom of the liquid reservoir.
VI) Estimated volume of liquid helium in the liquid reservoir.
VII) Phases of the operating cycle (see also fig. 1).

4. Experimental performance

Figure 3 shows measured cyclic temperature variations at the bottom of the expansion vessel and at the bottom of the liquid reservoir. For convenience, estimated pressure and liquid helium level variations are also shown. The cryocooler provides a good degree of inherent temperature stability. The observed temperature fluctuations at the bottom of the liquid reservoir were only 30 millidegrees, in spite of the 16 degree variation in the temperature of the expansion vessel. This stability is achieved without any electronic temperature regulation.

It was not possible to directly measure the amount of liquid helium in each of the vessels with our apparatus. We have estimated the amount of liquid produced by measuring the time required to boil it off by means of electric heaters. In a series of single expansion experimenta we observed that approximately 2 ml of liquid is produced in the expansion vessel. After a similar expansion followed by a 'transfer' phase approximately 1 ml of liquid had collected in the reservoir. The expansion vessel itself acts as a thermal diode and can retain its charge of liquid for 28 minutes in spite of the fact that its upper surface stays near 12K. That heat leak corresponds to 3 mW which agrees with the value calculated from the thermal conductivity through its thick steel walls. A low thermal conductivity between the top and bottom of the expansion vessel is important so that a pool of liquid may remain at the bottom for long enough to be 'transferred' to the reservoir.

The startup of the cryocooler requires 24 hours of operation of the two stage Gifford-McMahon cycle cryocooler in order to reach 12K. This is due to the massive regenerators which must be cooled. The startup time could be reduced somewhat by providing heat switches to improve the thermal contact to the regenerators. Once the 12K threshold has been reached full operation starts quickly with liquid helium remaining in the reservoir after a couple of cycles. The temperature stability in the reservoir improves dramatically after several additional cycles due to the accumulation of a sufficient depth of liquid helium.

The success of our cryocooler depends on the excellent thermal isolation provided by the thin wall stainless steel insulation tube which separates the expansion vessel from the liquid reservoir. The dimensions of this tube are given in table 1. With one end of the tube at 20K and the other end at 4.2K the theoretical heat leak by conduction through the steel is 0.4 mW and by conduction through the helium is 0.06mW. The liquid reservoir was observed to retain a charge of liquid for over two hours without replenishment. The liquid charge was approximately 2 ml, so this corresponds to a total heat leak of only 0.6 mW.

The cryocooler has been operated with a continuous heat load of 3 mW and it maintains a pool of liquid helium at all times. This power setting agrees with that expected from the latent heat of boiling of 1 ml of liquid every 15 minutes. Naturally, the heat load increases the temperature variation at the liquid reservoir. The maximum temperature variation is nevertheless limited by the boiling point of helium at the pressure applied. Additional temperature regulation could also be incorporated by controlling the pressures in the two gas lines.

The consumption of helium gas from the supply cylinder is such that the cryocooler can be operated for approximately 250 cycles from a laboratory 6 standard cubic meter compressed gas cylinder. With 15 minute cycles this corresponds to 60 hours of continuous operation. If the maximum cooling power is not needed the cycle time may be increased to 30 minutes to extend this period. Another advantage of this design is that cycling can be stopped in the primed state, phase (a), such that liquid helium may be produced at the touch of a button when needed.

5. Conclusions

A cycled adiabatic expansion crycooler which provides continuous cooling at liquid helium temperature has been demonstrated. Temperature stability of the liquid reservoir is very good because it is controlled by the boiling point of liquid helium. Unlike Joule-Thompson cryocoolers, this design does not have any small orifices prone to plugging. It also has no moving parts in the third or fourth stages. These features allow this crycooler to operate even with contaminated helium and make it highly reliable.

The cycled adiabatic cryocooler does not provide as much cooling power at liquid helium temperature as the Quantum Technology Corp. Joule-Thompson cryocoolers using the same two-stage Gifford-McMahon cryocooler. However, it does have its own domain of application where the inherent temperature stability and reliability of the cycled adiabatic cryocooler make it more advantageous.

6. Acknowledgements

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Table 1 - Helium liquifier dimensions

STAGE	TEMP. RANGE K	TUBE DIAMETER cm OD	TUBE WALL cm	TUBE LENGTH cm	MATERIAL	MASS gr
(A) EXPANSION VOLUME HIGH PRESSURE TUBING						
E1	300-70	0.48	0.09	500	SS	500
E2	70	0.95	0.15	23	Cu	90
E2	70	copper shot inside copper tube				30
E3	70-12	0.48	0.05	210	SS	130
E3	70-12	lead shot regenerator inside SS tube			Pb	75
E3	70-12	lead shot regenerator outside SS tube			Pb	775
E4	12-4	0.32	0.05	50	SS	20
Expansion volume	4.2	1.6	0.17	8	SS	65
(B) LIQUID RESERVOIR LOW PRESSURE TUBING						
E1	300-70	0.16	0.02	500	SS	50
E3	70-12	1.27	0.09	210	SS	550
E4	12-4.2	0.16	0.02	50	SS	4
E5	4.2	1		0.5	Pressed Cu powder	20
Insulation tube	4.2	0.64	0.02	14	SS	5
Liquid reservoir	4.2	2 ml volume			Cu	10

NOTES: - Expansion chamber volume = 10 ml.

- Low pressure and high pressure tubes are concentric heat exchangers at stages E1, E3 and E4.